STATE OF NEVADA
AGENCY FOR NUCLEAR PROJECTS/
NUCLEAR WASTE PROJECT OFFICE

NWPO-TN-005-90

NUCLEAR WASTE SHIPPING CONTAINER RESPONSE TO SEVERE ACCIDENT CONDITIONS: A BRIEF CRITIQUE OF THE MODAL STUDY

by

Lindsay Audin
Consulting Engineer
Ossining, New York

December, 1990

The Nevada Agency for Nuclear Projects/Nuclear Waste Project Office was created by the Nevada Legislature to oversee federal high-level nuclear waste activities in the state. Since 1985, it has dealt largely with the U.S. Department of Energy's siting of a high-level nuclear waste repository at Yucca Mountain in southern Nevada. As part of its oversight role, NWPO has contracted for studies designed to assess the transportation impacts of a repository.

This study was funded by DOE grant number DE-FG08-85-NV10461.

Contents

Executive Summary and General Conclusions 1
- Procedural Criticisms 1
- Highlights of this Critique 2
- Applicability to Future Shipments 3

Introduction and Overview 4
- Why a Modal Study? 4
- Cask Design Standards 4
- Cask Certification 4
- Risk Assessment 5
- The Modal Study: Purposes and Methods 5
- Potential Shortcomings 6

Critiques and Questions Concerning Potential Deficiencies 7
- Primary Sources of Criticism 7
- How this Critique Was Performed 7
- Examination of the Peer Review Process 8
- LLNL'S Responses to the Peer Review Process 11

Discussions of the Deficiencies 12
- 1. Data Creation and Analysis 13
  - Accident Rate Data 13
  - Distributions of Accident Severities 13
  - Quantification of Consequences 15
- 2. Cask Design and Response Assessments 15
  - Description of the Representative Cask and its Materials 16
  - Problems with the Cask Simulation 18
  - Final Comments on the Realism of the Modal Study's Cask 23
- 3. Accident Scenarios 24
  - 10CFR71: Starting at the Destination 24
  - Collision Simulated by Dropping 25
  - Interacting the Effects 26
  - Potential for Puncture 26
  - Concerns about Crush 27
  - Fire and "Smoke" 27
- 4. Spent Fuel Responses 29
  - Missing Sources of Radiation 29
  - How Much Cladding Damage and Fuel Leakage? 30
  - Other Possibilities for Fuel Damage 32
  - A Closer Look at Criticality 34

Relevance to Shipments to the Yucca Mountain Repository 35

Conclusion 36

References 37

Executive Summary and General Conclusions

The Modal Study (NUREG/CR-4829) attempts to upgrade the analysis of spent nuclear fuel transportation accidents, and to verify the validity of the present regulatory scheme of cask performance standards as a means to minimize risk. While an improvement over many prior efforts in this area (such as NUREG-0170), it unfortunately fails to create a realistic simulation either of a shipping cask, the severe conditions to which it could be subjected, or the potential damage to the spent fuel cargo during an accident. There are too many deficiencies in its analysis to allow acceptance of its results for the presumed cask design, and many pending changes in new containers, cargoes and shipping patterns will limit applicability of the Modal Study to future shipments.

In essence, the Modal Study is a good start, but is too simplistic, incomplete, outdated and open to serious question to be used as the basis for any present-day environmental or risk assessment of spent fuel transportation. It needs to be redone, with peer review during its production and experimental verification of its assumptions, before it has any relevance to the shipments planned to Yucca Mountain. Finally, it must be expanded into a full risk assessment by inputing its radiological release fractions and probabilities into a valid dispersal simulation to properly determine the impact of its results.

Procedural Criticisms

The Modal Study was tasked to be an independent verification of the hypothetical accident sections of 10CRF71, the existing framework of cask performance standards. Too often its investigation paralleled or copied aspects of those rules (e.g., sequence and types of accident stresses) for it to be independent of 10CRF71's portrayal of a worst-case reality. The implications of crush and puncture of the outer shell, for example, are almost completely ignored.

The Study itself was peer reviewed after its completion by two research groups (Denver Research Institute and Los Alamos National Laboratory) which were given only a draft of the Study's text to analyze. Many assumptions and calculations were made that were not visible or verifiable by the peer reviewers or the author of this report, nor were the Study's appendices complete (e.g., no coverage whatsoever of spent fuel damage analysis). As a result, the peer reviewers only spot-checked calculations they could readily replicate, and trusted the expertise of the Study's producers for almost all other analyses. This reviewer went into further detail in areas not touched by the peer review (e.g., interactions of stresses, radiological release calculations) and raised questions that can only be resolved by dialogue with the Study's personnel.

So many assumptions and analyses are missing from the text of the Study that it is unclear where engineering judgments end and actual mistakes begin. It is therefore possible that data which appear to be erroneous are simply the results of unacceptable (and hidden) assumptions. When coupled with the Study's often unclear presentation of its methods and resources, a proper review cannot be done. It should be noted that no other in-depth critique of the Study has been performed, and the many questions raised by this report (and those of the peer reviewers) should be seen as the basis for either a more complete investigation of the procedural details of the Modal Study, or as input to a new study of spent fuel containers and transportation accidents.

Highlights of this Critique

While there are many potential flaws, some are of greater concern than others. Accident rates, for example, are open to question because of deficiencies and applicability of available data, but such errors are less able to influence overall risk than some assumptions concerning the distribution of accident severities, or the various ways in which a cask could leak. Following are some of the problems that may have significant effect on the Study's final results.

- Cask design and accident parameters are significantly oversimplified. The use of strain as the primary variable to define damage does not reflect the results of scale model tests in which failures occurred at seals and welds, not at yield points in the main cask body. The use of mid-lead temperature during a fire conceals the potential for alloying and for cask/seal/fuel damage hours after the fire is out.
- A great deal of information was "created" to fill in missing data on the probabilities of different accident conditions. Some assumptions of random distribution may be invalid, while other judgments regarding severities are outdated or were never verified by experiment or independent expertise (e.g., likelihood and impact of high temperature fires). The absence of benchmarked tests greatly reduces the Study's credibility.
- The interactions of the stresses were not fully analyzed. For example, the presence of an empty neutron shield was found to greatly reduce heat transfer due to fire, but damage to the shield from an impact (resulting in reduction of its insulating capacity) does not appear to be covered in the impact-fire scenario. Similarly, the spent fuel itself was not included in the simulations, so damage to the fuel by a cask collapsing upon it due to sidewise impact was not analyzed. Such lack of interaction could greatly underestimate the heat available to cause damage to the outer shell (possibly leading to loss of the gamma shielding), or the potential release fraction of spent fuel nuclides.
- While admitted in the opening section of the Study, the failure to examine the impact of human error greatly limits the applicability of the analysis to the real world. Actual casks very similar to the representative container in the Study had many problems that should have been examined in the Study's simulations. Most of those deficiencies existed during numerous shipments and some applied to more than one copy of the design.

  They therefore could have been present during many of the scenarios in which the Modal Study assumed "perfect" construction and handling. Human error has proven to be the bane of the nuclear industry, so examination of only mechanical failure is a serious limitation in the Study.

- Computer simulations of cask impacts on a flat surface did not replicate a phenomenon known as "slap down" in which secondary impacts occur. Experimental results with scale models indicate that these secondary contacts (usually at different angles from the first) may experience greater strain than those of the first impact. The Modal Study's software was also inconsistent and limited in its ability to predict the degree of strain beyond a narrow range of severity. There is a strong need for experimental verification of the most vulnerable configuration of the cask at impact and the resulting strains/damage that occur.
- The treatment of spent fuel damage is too simplistic and is based on unrelated tests having little relevance. The sole basis for the release fractions due to impact is test data developed from thermal stress. As a result, the "worst-case" scenario for cladding damage amounts to only a single, 1/16-inch diameter, hole in each 15-foot long fuel rod. Release of re-oxidized fuel pellets is assumed not to occur based on tests where no oxygen was available, contrary to circumstances that would prevail in any cask release. Admitting that experimental data on spent fuel impact is lacking, the Modal Study proceeded with using nearly irrelevant information as the basis for its conclusions that very little radiation would escape the cask.
- The portrayal of the spent fuel itself was also deficient. A major isotope (americium 241) is missing from the truncated list of nuclides available after 5 years of decay, and the gamma output of the structural end parts of the assembly was disregarded. The first item could impact on the particulate hazard and the second on the exposure hazard after lead slump due to an endwise impact.
- Available data on cladding and fuel damage (both experimental and accidental) was not referenced or utilized, thereby limiting the depth of the analysis and the acceptability of the conclusions of accident consequences.

Applicability to Future Shipments

Higher fuel burnup rates, dry storage, rod consolidation and more assemblies per shipment will affect the radiological hazard of future spent fuel shipments. Solid (instead of water) neutron shields, thinner cask shells and use of uranium gamma shielding will greatly affect the response of new casks to impact and fire. The distribution between rail and road shipments may be greatly altered by rail availability at reactors and by erection of a monitored retrievable storage facility. The hazards of other materials shipped with or near spent fuel casks may affect the worst-case fire scenarios.

Taken by themselves, these factors could so alter the accident, cask and fuel characteristics that they alone would call for a new Modal Study. When combined with the deficiencies and uncertainties of the present Study, there can be little question of the need for a new, up-to-date, well-founded and properly reviewed Modal Study. The Nevada Agency for Nuclear Projects is developing a list of improvements for such a future study.

Introduction and Overview

Why a Modal Study?

The purpose of the Modal Study was to examine the validity of existing cask design and certification standards, via engineering analyses of the responses of a representative cask to transportation accidents. To clearly understand the direction (and criticisms) of the Study, some background on the procedures used in cask development is essential.

Cask Design Standards

Shipping casks for irradiated nuclear fuel are considered the primary barrier to a release of radiation in a transportation accident. A great deal of attention has therefore been focused on the design of these containers. While no design can withstand all possible accidents, federal regulations set cask standards that require containers not to leak significantly in the vast majority of accidents, including severe conditions involving fire and impact.

Those rules primarily define performance standards, i.e., the types of conditions that the package must survive. Exactly how those standards will be achieved is left to the designer. While the basic regulations have remained unchanged for over 20 years, several "guides" have been issued to formalize a common approach to meeting the standards. In addition to containing its radioactive contents during an accident, a container must maintain the ability to control criticality (i.e., avoid an accidental nuclear reaction) and limit routine emissions during transport. Finally, a cask design must accommodate the requirements of the transportation and nuclear industries in order to be commercially viable. Limitations on size, weight and internal configuration all come into play.

Cask Certification

Because of the potential for a serious health hazard if the spent nuclear fuel were to escape from the cask, much attention has been paid to proving the ability of the casks to contain radioactive materials and radiation during accidents. Due to the expense involved in destructive testing of actual casks (each costs on the order of a million dollars or more), federal regulations accept scale model or mathematical simulations of tests to verify the safety of a given design.

When a design is finalized, it is described in a "Safety Analysis Report for Packaging" (also known as a SAR or SARP), which follows a format suggested by a regulatory guide. If found acceptable, a license known as a "Certificate of Compliance" (CoC) is issued. Both documents usually include requirements for maintaining and inspecting the container at routine intervals to control its quality. Quality assurance during fabrication is handled by occasional federal inspections of the manufacturing facilities and documentation on materials and staff skills.

Risk Assessment

The basis for accepting the present cask design standards rests on the overall likelihood of fatalities due to cask leakage during spent fuel transit. This conclusion is developed by determining the probabilities of accidents sufficiently severe to release enough radiation such that, upon dispersal, there is a fatal inhalable concentration available to affect the public. The probability of accidents is assumed to be proportional to the number of shipping miles (i.e., the total number of trips x the length of the average trip). Using other statistical and analytical techniques, it is possible to calculate the chances that such accidents will occur during the likely history of spent fuel shipping. If, for example, during 50 years of shipping, only one chance in 40 of a single death is expected, it could be said that only one radiation death in 2000 years (50 x 40 = 2000) is probable. Arriving at such a number involves the multiplication of numerous figures, some very high (e.g., shipping miles) and some very low (e.g., portion of radiation releasable in harmful form). The final result, called "risk" (e.g., one death in 2000 years), is the mathematical product of the probability of an accident and its consequences.

Implicit in all such risk analyses is a grasp of the way probabilities and consequences are calculated. Virtually all studies equate the accuracy of the methodologies involved in quantifying these two factors, as though it were a given fact, regardless of the uncertainties and differences in methods. Any "gray" areas are resolved via "conservative" assumptions, i.e., that the worst case will occur, so that minor methodological errors are avoided in reaching the final conclusion. Such "gray" areas include the validity of accident rate and severity data, and the response of the fuel rods to heat and shock. Defining that credible worst case is, in itself, an uncertain task involving numerous other assumptions.

To appreciate and simplify the difficulties involved, it is often best to look only at the range, in factors of 10 (called "orders of magnitude") that uncertainties could yield in a given area. For example, truck accident rates vary from state to state and even route to route, but the data (from the best to the worst routes) may vary only by a factor of 5 (the worst case is "only" 5 times worse than the best). Thus, one could say there is an uncertainty on the order of .7 orders of magnitude (i.e., 10 to the .7 power is 5). Underreporting of severe accidents has been found (in the DOT accident base) to be as high as 90%[1], so only one out of 10 severe accidents may be listed. That yields another order of magnitude of uncertainty. Since orders of magnitude can be added, a range of 1.7 orders of magnitude is the maximum range across which reasonable people should differ in severe accident rates. By comparison, the portion of fuel released in an accident could vary over several orders of magnitude, depending on the scenario involved. Normalizing all factors into such ranges of uncertainty gives perspective to other variables, as well.

The Modal Study: Purposes and Methods

The lack of applicable full-scale testing has led to criticism of the basic standards as being only theoretical, and meeting them as insufficient to prove safety. To answer these questions, several studies have been performed to better assess the capabilities of containers that meet those criteria. The most recent attempt is NUREG/CR-4829, "Shipping Container Response to Severe Highway and Railway Accident Conditions," also known as the "Modal Study." Under commission to the NRC, Lawrence Livermore National Laboratory (LLNL), a federally-sponsored facility in California, sought in 1986 to determine two basic characteristics involved in this issue:

- the distribution of accident severities, and
- the response of spent fuel and casks to those conditions.

To do this, LLNL had to "fill in" a great deal of missing information on accidents by using statistical techniques and engineering judgments to "create" a more complete data base. Since no experimental work was to be performed, a simplified cask design was also created to be used as input to various computer simulations of impact and fire. Finally, numerous simplifying assumptions were made to focus the study on the adequacy of existing standards. For example, LLNL found it necessary to assume that its cask was manufactured, maintained and loaded exactly as outlined in its design specification, as is assumed by federal regulations but not always realized in the field.

It was also necessary to restrict the number of critical variables to be examined when characterizing the severity of an accident. While the regulations discuss the height from which a cask was dropped onto a theoretically unmovable surface, for example, LLNL did not find this variable to be useful in determining what accident conditions would yield equivalent damage. It was concluded that strain on the inner shell (an engineering concept that describes the degree of stretching or denting) and temperature at the mid-point of the gamma shielding would be used instead. Cutoff points for these variables were then determined, beyond which it was assumed that the cask would release some of its contents to the environment. The representative cask would then be subjected to the various conditions and analyzed to determine the type and severity of accident necessary to attain or exceed these cutoff points.

By combining the results of its findings on the likely distribution of accident severities with the cask responses to such conditions, it was then possible for LLNL to create a matrix of data that correlated the probability of a set of accident conditions and the radiation releases that would result. These correlations were then compared to similar data developed in a 1977 study, NUREG-0170, also called the "Final Environmental Statement on the Transportation of Radioactive Material by Air and Other Modes." That study was the basis of NRC's conclusion that overall risk (that is, probability multiplied by consequences) of shipping spent fuel was low enough to require no changes to cask design regulations. If the LLNL work yielded comparable results, then the conclusions of NUREG-0170 could be considered reaffirmed.

While not utilizing the same input data or output framework, LLNL translated its findings into a form similar to those of NUREG-0170, and concluded that the overall risk was even less than previously believed; thus, the NRC rules remained acceptable.

Potential Shortcomings

Critics have examined the LLNL work and found deficiencies, some minor and some potentially serious. They range from the validity of the data input to the simulations, to the description of the accidents and the responses of the cask and fuel rods to heat and shock.

It should be understood that the task undertaken by LLNL was, in some ways, herculean: lacking data to analyze, or funds to perform tests, it developed a framework for furthering the analysis of hazardous materials shipments. For that work alone it is to be commended. It is hoped that the deficiencies noted in this report can be ameliorated, and the LLNL assumptions now outdated by changes in cask design can be corrected, so that the debate over cask safety may eventually result in an assessment methodology acceptable to all concerned parties.

Critiques and Questions Concerning Potential Deficiencies

Primary Sources of Criticism

The view of three groups of critics are reflected in this critique:

- the two peer reviewers: Denver Research Institute (DRI) and Los Alamos National Laboratory (LANL)
- The Western Interstate Energy Board reviewers
- the author and reviewers of this critique.

An attempt has been made to incorporate all of the major questions raised by the above, in many cases consolidating them to fit the framework of this report. Since many duplications occurred, no indicator of authorship is given unless important to the credibility of the question.

How this Critique Was Performed

A comprehensive review of the relevant literature was conducted, including a careful reading of the Modal Study, previous risk analyses, the peer reviews and related materials. In addition, a Freedom of Information Act request was filed with the NRC on all correspondence and contracts between the peer reviewers and NRC. It is noteworthy that the overview document to the Modal Study (entitled "Transporting Spent Fuel," NUREG/BR-0111) indicated that all such documentation existed in the NRC's public document room but, even two years after completion of the Study, no effort had been made to allow public access to the peer reviews, nor had anyone sought such access. References cited in the Modal Study and the peer review documents were also obtained and incorporated into the investigation.

The simplifying assumptions and calculations (along with uncertainties due to items not considered by the Modal Study) were then evaluated. Recent changes in cask design, payload and neutron shielding, plus past errors in manufacturing, cask loading and handling were all examined for their potential impact on the LLNL analysis.

Finally, the major and minor questions and perceived deficiencies were sorted into groups to facilitate production of a review document. A draft was produced and reviewed for completeness and clarity prior to offering it to other UNLV consultants for comment. Many minor criticisms were deleted at this last stage to highlight the most important questions. It should be understood that the appendices of the Modal Study do not offer sufficient data in many areas to allow proper evaluation, and actual interview of the Study staff appears to be the only sure method to ascertain the many hidden assumptions that were apparently made to arrive at some methods and conclusions.

Examination of the Peer Review Process

Two research organizations examined the Modal Study draft report: Denver Research Institute (DRI) and the Los Alamos National Laboratory (LANL). DRI is affiliated with the University of Denver and LANL is a DOE-sponsored facility specializing in nuclear weapons design and development. Neither has any involvement in shipping commercial high level nuclear waste or in the utilization of spent fuel casks. Unlike a member of the nuclear industry, neither had a vested interest in supporting the results of the Study. LANL was a subcontractor to DRI to review the computer simulations used in the structural analyses of the Study (primarily Appendix E). The choice of DRI was quite simple: it had expressed interest in past NRC requests for proposals (RFP), and the only other agency considered was the University of Washington at St. Louis (UW). NRC files show only one response to its RFP, that being from DRI, though another from UW is mentioned in other correspondence. An NRC panel made the choice and there was apparently no requirement for competitive bidding or other rules for selecting a peer review contractor.

While DRI's comments were candid and often critical, it was obvious that it focused primarily on the mechanical aspects of the analysis. Much less attention was given to the sections dealing with probability, accident scenarios and spent fuel responses. This is understandable since the interests and experiences of the DRI personnel (based on the resumes and published papers listed in their proposal) were almost entirely related to mechanics and ballistics, and not transportation or radiation. Any analysis of the peer review must also keep in mind that it examined a somewhat different document than was published. A point-by-point comparison between the final edition and the peer review found, however, that many minor problems cited by it were corrected. Major criticisms, especially by LANL, were either not accepted or else were handled by editing and the addition of text. Most of the fundamental disagreements remain, and this review focuses primarily on them.

Much criticism was leveled at the format and order of presentation, which the principal reviewer (Myron Plooster, a physicist) described as "obscure and difficult to follow."[2] Perhaps most disturbing was the large number of numerical errors, some of which were typographical but many may have been calculational. Plooster states: "it is a certainty we have not found them all. We were still finding numerical data errors in the last week of this review effort." An extensive letter preceded the review report and analyzed an "apparent anomaly in the frequency distribution of thermal damage to truck casks."[3] While he felt that the error would not have a major effect on the overall risk, it did reveal that the calculations may not be entirely reliable. LLNL's response did not specifically acknowledge that anomaly, but instead agreed that there were "input errors" to the thermal analysis simulation.[4]

Several items stand out from the review that demonstrate its lack of depth, which appears to be as much related to the small size of DRI's grant as to the limited relevant experience of the reviewers.

DRI apparently was given only the text of the draft report. No actual calculations, simulation inputs or list of assumptions were examined, beyond what is found in the text. While discussing the analytical (versus experimental) approach taken by LLNL, Plooster states:

> "The analytical approach has the disadvantage that the reader cannot follow the detailed path between input and output, because of the number of complex computations connecting any input datum with the final results. This approach requires an implicit trust, on the part of the reader, in the quality of the programs used. Having said all this, some definitive experiments, or reference to such experiments, would greatly enhance the credibility of the work."2
>
> In its comparison review to DRI's paper, LANL echoed this view: "The credibility of the structural response calculations supporting this work can be improved [by]...benchmarking calculations against actual experiments. (Saying that Sandia used a code similar to NIKE-2D to calculate the response of full-scale casks used in crash tests is a rather weak substitute for benchmark calculation!)"5

In effect, the reviewers examined nothing more than what LLNL chose to put into its report, and had to make of that what they could. While there are no laws governing peer review, it is not unusual in other professions to examine the full line of researcher's calculations and all of the assumptions, not just those considered worth mentioning.

Many of the more mundane criticisms mentioned by others were also raised by DRI (e.g., American Petroleum Institute (API) accident data, applicability of California highway characteristics), but most of its focus was on the mechanical engineering considerations and how other aspects of the analysis affected them. When examining severe accident scenarios, it felt that a sidewise impact of a truck cask on an abutment or concrete column should have been investigated since "the impact force would be concentrated on only the central portion of the cask, and the ends of the cask could 'wrap around' the structure. In such an impact, bending stresses severe enough to cause tensile failure and rupture of the cask might be achieved." While acknowledging its low probability, DRI felt it was a "plausible accident with the potential for a major radiological hazard." It also expressed concern about the likelihood of such severe accidents:

> "The inhomogeneity and incompleteness of accident data bases makes this the greatest source of uncertainty in this study, in our opinion. The most severe accidents, the only ones with the potential for serious risk to the public, are out in the 'tails' of the probability distributions, where statistical uncertainties are greatest."2

And because of its limited examination capacity, "it is not possible to verify any of [the probability analysis] independently; one has only subjective judgment to rely on in evaluating the results." This type of uncertainty permeates the report, leading Plooster to state at one point that "the more closely one reads this report, the harder it is to follow." And after trying to correct the report's many numerical typographical errors, he finally concludes that "we do not have enough information to verify [the Study's] numerical data."

Other problems with the completeness of the analysis were raised (e.g., train sill impacts were always side-on only, always perpendicular to the cask axis), but DRI stopped short of venturing an opinion on the importance of the problems it perceived. Instead, it said "the report as it now stands needs to go through a major quality control process... Every number in this report needs to be checked against its original source... Any scientific journal or publisher receiving a document in this condition would have rejected it out of hand." The public record on the Modal Study indicates that no such detailed followup was ever performed. Nevertheless, with its admittedly limited perspective, DRI felt that "from a technical standpoint, the report is basically sound. No flaws have been found which cast any significant doubt on the major conclusions."

This tune changed later, however, after DRI received the LANL companion report, which also focused mainly on the structural analysis. DRI's lack of knowledge on real cask behavior became obvious in its cover letter to NRC:

> "If the Battelle and Los Alamos scale model experiments [covered in the LANL report] are correct in showing that closure and weldment failure are the most probable structural failure modes, then the foundation of the Livermore analysis, and the use of strain as the response variable, is in question."[6]

The LANL report used two references[7,8] to demonstrate its point that results of experimental tests on cask failure disagreed in some ways from LLNL's theoretical conclusions:

> "In these tests, failure (leakage) was never caused by excessive strain in the parent material but rather at welds or because of excessive deformations at seals."[5]

Both test series in LANL's references used carefully designed and fabricated scale models in 30-foot and 40-inch drop tests, as per 10CFR71. LANL felt that LLNL's use of "conservative" material properties did not address either source of failure.

Perhaps the most telling comment by LANL concerned the pervasiveness of LLNL's choice of strain as the operant structural parameter. LANL points out how many aspects of the Modal Study are touched by that (possibly erroneous) assumption:

> "The difference [between closure failure and maximum plastic strain] can be significant in picking a generic cask since closure failure may be more dependent on peak impact force. Peak impact force would be larger for the 'harder' shielding materials, such as uranium. "The point is that once this choice [of maximum plastic strain] is made in Section 2, the remaining results are totally influenced by it."[5]

LANL also questioned the validity of some of the impact simulations (e.g., IMPASC and NIKE) and, in several instances, reacted negatively to the Modal Study's claims of benchmarking. Aside from the previously mentioned attempt to cite a Sandia analysis that used a different computer code, LANL points out that:

> "IMPASC overpredicted the endwise impact calculation for a truck cask from NIKE by 17%, yet underpredicted the rail cask response by 20%."[5]

Typically, a simulation system will do one or the other, but doing both reveals inconsistencies either in the program or its input data. LANL also felt that the comparison between the strain determined in a physical test and that found from the equivalent damage method was "so poor that some explanation is needed." LANL concluded that "if these results are correct, the equivalent damage technique does not appear to be the best method to use for estimating the effects of impacting real surfaces." That method served as the basis for eliminating some scenarios and reducing the probability of others because their speeds were (from LLNL's perspective) unrealistically high. Replacement with a different technique could yield different results than those portrayed in the Modal Study.

LANL refers to a Battelle Columbus Laboratory study (BMI-2039) of lead-shielded scale models in drop tests, as both a resource for possible benchmarking and as evidence that closure and weldments, not excessive strain, are the most likely source of failure. A second reference discussed uranium-shielded scale models in drop tests. Both studies were obtained and found to strongly support LANL's assertions about weld and closure failures. Each also covered the problems inherent in modeling drops on corners: such tests usually involved secondary impacts, none of which were analyzed in the Modal Study. As discussed in more detail later in this critique, there is a phenomenon (sometimes called "slap down") in which kinetic energy is transferred from the cask end that first strikes a surface over to the opposite end, which is then accelerated as it revolves around the first contact point, or its center of gravity. The references indicate that bending stresses resulted and that the measured strain in the second impact (at the opposite end) exceeded that of the first. This action complicates the modeling of impacts used by LLNL.

While questioning its basic methodology, LANL stopped short of attacking the Modal Study's general conclusions, however, by stating:

> "In general, the reviewers believe that the overall probability conclusions from the study will not be changed significantly by any issues raised in this review, but do believe that the supporting analyses can be stronger."

LLNL'S Responses to the Peer Review Process

Many of LLNL's responses to the points raised by DRI and LANL were either not direct, or else were not substantiated. When it had no good answer, it agreed that more work was essential to settle the problem but blamed "budget and schedule constraints." Many responses began with "we believe," or claimed "conservatism" covered the situation, or else were simply statements that had no more backup than was found in the text. LLNL denied that the tests used in BMI-2039 could be used for benchmarking and provided a reference of its own to point out the difficulty in comparing computer output with test data, which it indicated was often quite inconsistent. This reference (LASL-3306) does support LLNL's view of the problem but likewise discusses the "slap down" phenomenon. It concludes that "none of the [analytical] methods could be substantiated by dynamic measurements made in experiments... most of the methods seemed to be inadequate for the goal of experimental substantiation."[9]

It also pointed out the complexity inherent in determining the most vulnerable drop orientation when secondary impacts were possible. LLNL appears to use this reference to tell LANL that "your way is no better than mine, so therefore my way must be acceptable." While LASL-3306 does criticize past experimental efforts, it definitely does not support the Modal Study's present theoretical framework.

In essence, these "dueling references" support the notion that much more experimental testing is needed to obtain a realistic perspective on the highly theoretical analyses used in the Modal Study. This discussion indicates that the state of knowledge (at least at the time of the Modal Study) necessary to demonstrate cask safety may be deficient.

LLNL appeared to denigrate the views of LANL's references regarding failures at seals and welds. Without citing any basis for its view, LLNL repeated its assumption that "the seal will not fail at stresses less than yield," though that is apparently what occurred in Battelle's tests. It also stated that "ideally, weld joints should not be present in these areas [near the end closure] where high local strains can occur," though there is no NRC regulation or guideline covering that issue. Focusing again only on the inner containment, it concedes the possibility of local cracking but says "it is not likely that the inner containment will completely rupture." No analysis was made of the potential for lead loss through such failures during a fire. LLNL pointed out that the scale model tests cited in BMI-2039 by LANL were not licensed casks and that a "cask design that results in a 1% lead slump for a 15 foot drop would likely not be licensed or permitted to transport spent fuel." This reveals an interesting aspect of LLNL's response. While LANL had said that its "reference 1" (i.e., BMI-2039) discussed such a lead slump test, it did not say that any of the tested scale models in that study experienced such a result. Examination of BMI-2039 shows no mention of a 15 foot drop test. Apparently LANL's commentary meant to cite a reference in BMI-2039, since lead slump was a topic of that reference. It is unclear how LLNL could have misunderstood LANL, unless it never actually examined BMI-2039. LLNL summarized its responses by re-citing the peer reviewers' comments that their criticisms did not substantially question LLNL's major conclusions.

The reader is left with an uneasiness about the subjective manner in which analytical disagreements were seemingly settled. No calculations were mentioned or shown, and no sensitivity studies were performed to assess the impact of possible deficiencies. Normal peer review processes, such as for a professional journal, are much more rigorous. By contrast, this process involved only an examination of a completed text, without its backup calculations, by agencies with either very limited experience or a narrow focus. It would be difficult to characterize the results as having any significant depth, or to accept them as sufficient confirmation of the Modal Study's credibility.

Discussions of the Deficiencies

Four categories of problems were found:

1. data creation and analysis
2. cask design and response assessments
3. characterization of accident scenarios
4. assumptions regarding spent fuel and its response.

The remainder of this report focuses on these issues.

1. Data Creation and Analysis

Accident Rate Data

The starting point for all accident analyses is an accident rate, usually expressed as a number of accidents per million miles of shipments. The Modal Study used an accident rate from the American Petroleum Institute (API) ostensibly because it covered shipments in containers of size and weight similar to spent fuel casks. The API data was also "judged to be more reliable" than data from the Bureau of Motor Carrier Safety, though no basis was given for such judgment. Rail accident data was taken from the Federal Railway Administration (FRA). Roadway conditions that are related to the types and severity of accidents were developed using California highway characteristics.

Several comments by critics were made on this data, the most cogent of which related to the API and FRA information. While the distribution of physical characteristics along California highways may differ somewhat from the rest of the country, it is unlikely to have a serious effect on the distribution of accident types since, on average, the incidence of grade crossings, etc. was found to be about the same as the average mile of national highways. On the other hand, the typical petroleum shipment (usually gasoline or fuel oil) is quite short (28 miles)[10] and occurs in an urban or suburban area. This makes sense because most petroleum products are moved long distances by pipelines or railroads, not motor vehicles. The accidents involved are therefore likely to be at lower speeds and on local roads. Reportage to API is also voluntary: "inputs are what member companies choose to report," according to DRI. LLNL responded by stating that it believed, because a hazardous material was involved, that reporting was better than other data bases and that travel on non-interstates would yield a conservative accident rate. While this latter fact may be true, the former is not. The United States Department of Transportation (DOT) maintains a system which requires, by law, the reporting of accidents involving vehicles carrying hazardous materials. Careful checking by both critics and federal analysts found that this data base was missing up to 90% of all such accidents, and perhaps 70% of the most serious cases.[11] The truck accident rate could then be low by nearly an order of magnitude (i.e., a factor of 10).

Rail data does not fare much better. A recent study by the U.S. General Accounting Office (GAO) found that "FRA has little assurance that its injury and accident data base is reliable because the railroads GAO visited were not reporting accurately or completely."[12] The degree of error for railroad data was less than that found for highway, but the sampling was limited, so the results could not be used as a correction factor.

By itself, this one source of error does not suffice to cast serious doubt on the results of the Modal Study. It does, however, reveal a naivete about the realities of the shipping world.

Distributions of Accident Severities

To develop the spectrum of accidents involving impact and fire, two data bases were used: impact data came from state and federal agencies' information on actual accidents, while fire data came from a previous analysis that "created" information by statistical techniques and judgments. The two data were mixed together by assuming a random distribution of fires within the types of impacts that could occur. The lack of real information precludes use of a better data base, but the results should be tested against some other smaller body of data where both impact and fire are known, in order to see if the distribution bears any resemblance to real circumstances. Such benchmarking would add credibility to the Study's assumed distribution of severe accidents. While such data may not be readily available from domestic sources (but may be available from other Western countries), there is no indication that LLNL made any attempt to verify its combination of thermal and impact data.

An example of the potential error that can result from an automatic assumption of randomness is as follows. Since highway routes for spent fuel shipments will, according to a study by the National Academy of Sciences[13], funnel down to a few major corridors, the likelihood of a truck fire involving another vehicle would be affected if that same corridor was commonly used as a prime route for flammable materials. An assumption of a random distribution of highway accidents involving fire would not be sensitive to route funnelling, but benchmarking against actual data on those corridors might reveal if the likelihood of fire was greater than the national average. It should be noted that past spent fuel shipments utilized only a small portion of the national highway network, but independent analysis of DOT data[11] found that nearly half the hazardous material accidents (most involving flammables) occurred on those spent fuel routes, probably because those routes link numerous chemical plants using those materials. It would also not be surprising to learn that truckers who routinely exceed the speed limit do not report that fact, especially if involved in an accident, or that long fires are not randomly distributed among the various collision speeds - but the Modal Study's randomized data appears to ignore those possibilities. Benchmarking could reveal such possible methodological errors.

LLNL did attempt a benchmark of sorts by comparing the results of four recent severe accidents with its own scenario analyses. It is interesting to note that all four occurred between the times NUREG-0170 and the Modal Study were performed and were, in some cases, worse than those previously considered the worst likely to occur. Is it possible that larger vehicles, more hazardous cargo, deregulation, etc., are creating more opportunities for severe accidents? The Modal Study implies, because its work was not contradicted by this small sampling of reality, that the casks are safe. The Study does not, however, consider other real hazards, such as stationary fuel or chemical tanks, that could yield much more serious consequences than those modeled by LLNL. Just such an accident occurred recently in Ohio when a burning butane tanker started a fire in a chemical plant near the railroad tracks[14]. And just as accidents of greater severity occurred after NUREG-0170, worse accidents have occurred since the Modal Study. A train derailment in the United States led to damage to an underground gasoline pipeline adjacent to the railroad. The pipeline later exploded, fortunately not while a train was passing[15]. Such a pipeline could provide an immense supply of thermal energy, leading to a very large fire of long duration. Only a few weeks later, this idea was proven when a leaking natural gas line in the Soviet Union exploded as a train passing nearby ignited the fumes, creating probably the worst rail fire in history[16]. The co-location of rail lines and pipe lines is not random: many use the same rights-of-way. Such real world considerations are absent from the random distributions in the Modal Study's fire analyses.

LLNL's methods of data creation for details of accidents, such as the distribution of impact angles, distances from a fire, etc., cannot be compared to real accidents, however. Actual data is clearly lacking and benchmarking would not be possible. On the other hand, an assumption of random distribution of impact angles does not reflect any effort to model the effects of tiedowns or other factors that could, in reality, skew the data. Proper modeling of this distribution could be important since experimental data indicates that impact at some angles (other than at a right angle) may be more likely to yield puncture of the outer shell of a container.

It is essential that a sensitivity analysis be performed to assess the order of magnitude implications of such assumptions. At the very least, a comparison with other studies that utilized different methods when examining spent fuel accidents (in some detail, unlike NUREG-0170) could shed light on the possible limits of the Modal Study's data creation procedures. Unfortunately, LLNL did not do so.

Quantification of Consequences

The data covering the choice and quantity of isotopes is also open to some question. Table 8-1 lists "only the specific isotopes that are important in performing a radioactive release evaluation." Comparison to other studies of spent fuel accident consequences[17] indicates that LLNL truncated a much longer list, but no criteria are given for its choices. While most of the missing isotopes are present in only small quantities or are not as dangerous as those in LLNL's list, americium-241, a daughter product of plutonium-241, exists in significant quantities and is as lethal as any plutonium isotope. Americium-241 would be of particular concern in shipments of older, high-burnup PWR fuel. Also missing is the cobalt-60 residing in the metal frames that hold the fuel rods. While not involved in a release of material, it would provide direct exposure in areas of lead slump. The absence of these isotopes could seriously underestimate hazard. These deficiencies are discussed further in the section on spent fuel and its responses.

The use of curies in various figures in chapters 8 and 9 conceals the hazard involved because it does not reflect the danger of a curie, which will vary from one isotope to another. Much of the danger comes from particles of plutonium, yet in the Modal Study's case, no more than 7.22×10^{-2} curies will be released, a number that may seem very small to the lay reader. Use of other units instead of curies is essential to yield data comparable to other studies, and to give a clearer picture of the possible hazards involved. Use of curies in a radiation spill is about as clear to the lay public (and many emergency response personnel) as would be the use of moles (i.e., gram-molecular weights) to describe the release of a poisonous quantity of chlorine gas.

2. Cask Design and Response Assessments

The Modal Study assumed a lead-lined cask with steel inner and outer shells, surrounded by a water neutron shield. In a preliminary analysis, LLNL concluded that this configuration was the most vulnerable to impact and fire. Further study would then be automatically conservative. A second level of analysis developed a more detailed version of the cask, using materials and dimensions nearly identical to the NAC-1 container, a truck cask designed for shipping one PWR or two BWR fuel assemblies This similarity is ironic in light of the history of the actual NAC-1 casks. The reader is directed to "A Review of the Effects of Human Error on the Risks Involved in Spent Fuel Transportation," prepared for the Nebraska Energy Office in 1987, for background in this area.

Description of the Representative Cask and its Materials

Numerous simplifying assumptions accompanied the cask analysis, several of which are best understood by a brief description of the cask materials and their responses to heat and force. Readers with a working knowledge of cask design may skip this discussion and proceed to "Problems with the Cask Simulation."

The Neutron Shield

The water neutron shield assumed by LLNL has been the most common type used on casks in the past. The most important aspect of it in the Modal Study, however, is its absence. The purpose of the water is to absorb neutrons during routine handling and use of the cask. Loss of the water may increase the level of escaping neutron radiation by a factor of 20 or more, but the final result is not considered by the NRC to yield a significant health impact. 10CFR71 allows such increases in the case of an accident. To their credit, the engineers at LLNL created a reasonably accurate thermal simulation of a water neutron shield after its water was lost, a likely event when heat from a fire causes the water to expand and/or boil, opening a pressure relief valve. The result is a dead air space between the outside skin of the cask and the cask's outer shell. That space would act like an insulator, much like the evacuated region in a thermos bottle. LLNL appears to have assumed that this insulating property remains intact, even after impact with other objects.

The Steel Shells

LLNL adopted two variables to describe the response of a container: strain on the inner steel shell, and the temperature at the mid-thickness of the lead shielding. While temperature is a commonly understood measurement, strain is not. It its simplest form, strain is the degree of elongation of a material prior to its failure. Many metals (steel included) will stretch when subjected to sufficient force, and generally do so in three steps. To grasp this phenomenon, consider a coil spring. Pulling on it yields an increase in length, and releasing it results in restoration of its original shape. This type of behavior is called elastic strain. Various types of steel can be stretched about .2% and still remain elastic. Now imagine pulling so hard on the spring that it began to lose its coiling, remaining stretched out of shape. That is analogous to plastic strain in steel: from .2% to 2%, it takes a gradually increasing amount of force to yield a permanent deformation. In the final stage, pulling a little harder will yield much greater elongation, between 20% and 30% beyond the original length, followed by cracking and breaking of the steel[18]. This second stage of plastic strain is one of the most valuable characteristics of steel: even under large forces, it does not break, but rather dents or stretches significantly, maintaining much of its strength until it has become quite distorted. Personal experience in a metals laboratory gave this writer the impression that some steels act like a "super taffy," when pulled sufficiently to cause plastic strain. Machining, cooling, alloying or repeatedly stressing steel can reduce this plasticity, however, so assuming its presence requires detailed knowledge of the mechanical history of the metal and the conditions existing when the force is applied.

Lead Shielding

Lead also has unique properties when subjected to severe conditions. Due to its high density and softness, it can act like baking dough when it is dropped: it will slump in shape under its own weight, spreading out in all directions. It also melts at a relatively low temperature (about 620°F), soaking up a great deal of heat at high temperatures, instead of merely conducting it. The lead then acts like a temporary insulator due to these (and other) properties. Lead also expands when it melts, and it was not unusual for lead-shielded casks to have empty space available to allow expansion, thereby avoiding pressurizing the cavity between the inner and outer cask shells. Other shielding materials (such as depleted uranium) are harder and do not readily melt, and they react quite differently to heat and shock.

Penetration Sub-Systems

Several penetrations through the ends and/or shells of a cask are common in a spent fuel cask. Most are essential to allow draining of spent fuel pool water when the cask has been loaded. It is typical for drain and vent valves to be installed by drilling into the shells and welding tubing and/or valves into place. In the past, a pressure relief valve was also included to relieve a water-filled cask pressurized by a fire. Such valves will probably be unnecessary for casks filled with inert gases and only residual amounts of water. The bottom end of a cask may be attached by welding it after machining its mating surfaces and drilling holes for alignment pins (attached to the inner and/or outer shells). Finally, lifting trunnions (stubs near the ends of a cask) may also be attached by cutting into the outer shell and welding into place. None of these penetrations were modeled by the Modal Study analysis.

Impact Limiters

At both ends of the cask, relatively soft shock absorbers, called impact limiters, are attached (usually by bolts into the cask lid and its bottom). Made of crushable wood, honeycombed aluminum or similar materials, they are designed to reduce the deceleration of a cask prior to impact. They protect the ends of the cask but offer no protection from sidewise impacts.

The Cask Seal

Finally, there are seals and bolts at the mating surface of the cask lid and its body. The seals are often a flexible elastomeric material that assumes the shape of the channels cut into the lid and body, much like the rubber seal at the top of a thermos bottle. While capable of maintaining their seal up to about 500°F, these materials break down at higher temperatures. Some metal seals can withstand temperatures in the range of 1000°F, but may require replacement with each use and are not favored due to this increase in maintenance. The Modal Study assumed seal failure in the 500°F to 600°F range.

Problems with the Cask Simulation

There are at least three basic problems with the Modal Study cask analysis:

1. its portrayal is seriously outdated by changes in cask design and payload
2. it does not reflect details of construction that create areas and points of vulnerability
3. it fails to account for human errors in cask fabrication, loading and maintenance that could easily compromise cask integrity.

This section will examine the impact of these deficiencies as they affect each of the previously discussed structural parts of the cask. The reader should note how a deficiency in one area creates conditions not examined in other areas. There are major synergistic effects inherent in the problems, and the Modal Study failed to model them, thereby greatly oversimplifying many aspects of its accident simulations.

The Neutron Shield

Almost all new cask designs (and all those proposed so far by the DOE) utilize solid neutron shields on the exterior of the cask outer shell, as versus older designs that used circumferential water tanks. Some are composed of organic materials high in hydrogen content (the key ingredient to shield neutron radiation) that, while not flammable, may vaporize or break down at high temperatures. They are not designed to resist either heat or impact, but instead exist as a means to keep routine emissions at regulatory levels. It therefore cannot be assumed that their presence will have any mitigating effect on heat transfer. This is important because the dead air space left by the empty water neutron shield modeled by LLNL cuts the heat transfer rate into the cask by over 70% (see pp. 6-33 to 6-39 of the Study). Since the time to reach lead melt is roughly proportional to this rate, it is possible that lead melt for a truck cask could be reached in about 20 minutes instead of 1.08 hours (calculated by LLNL), if the dead air space was lost. Seal failure and fuel rod damage may then occur earlier, as well. In realistic terms, this means that a smaller amount of flammable material is needed in an accident to melt the lead and yield high cask temperatures. This could increase the probability of an accident with severe consequences.

Another aspect of LLNL's treatment of the neutron shield regards its capacity to retain its shape when the cask is struck by an object or the cask strikes a flat surface. The outer layer of the shield may be punctured, torn or flattened, contacting the outer shell of the structural part of the cask. Any remaining dead air space on that side will be further reduced if the cask rolls or contacts other obstructions since there is only minor structural support for the neutron shield. The NAC-1 cask, for example, utilized heat transfer fins connecting the outer shell of the cask with the outer layer of the neutron shield. Such fins were designed to conduct heat away from the fuel if it was hot (typical of fuel only recently removed from a reactor), but would also act to conduct heat from a fire into the cask, thereby negating some of the insulating effect of the dead air space.

It should also be noted that, while only a thin dead air space will provide insulation, any puncture of the neutron shield will allow entry of hot gases into the empty shield, thereby nearly eliminating the shield's insulating capacity. While only a portion of the insulating space may be lost when the shield collapses, that would cause very uneven heating and expansion of the lead, not necessarily near the volume allowed for such expansion. Similarly, impact by a train sill or other hard object could rip away part of the outer layer of the neutron shield, once again creating a pathway for increased (and very uneven) heat transfer. When LLNL examined lead expansion in general, it found that it would yield slight warpage of the inner and outer shells but not enough to create major strain. This may be acceptable when it is assumed that the lead melts evenly throughout the cask, but not necessarily in cases when the expansion is local. Any localized weakness in the shells due to welds, penetrations, etc. could be affected by this local expansion.

An example of this phenomenon occurred during the 1978 Sandia fire test. An outer shell cracked in two places, creating a path for loss of molten lead. The lead had expanded and pressurized the gamma shielding cavity because the manufacturer had failed to drill holes into an adjacent empty space designed to allow for expansion. The shell was locally weakened by a series of welds that used welding rods contaminated with minute amounts of copper[9]. This actual response is a good example of the potential clashes between reality and the Modal Study.

The Outer Cask Shell

The regulatory stresses outlined in 10CFR71 include a drop onto a flat, unyielding surface followed by a second drop onto a steel stump. The Modal Study examined the strain that would result from such theoretical encounters and attempted to find "real" structures that would yield equivalent damage. Impact onto a real flat surface (earth, rock, etc.) could provide similar strain, depending on the impact velocity and the hardness of the surface. The Model Study concluded that most surfaces were too soft to cause such damage, unless the cask were moving at an unrealistically high speed. Rock and reinforced concrete surfaces would, at a realistic speed, provide similar strain.

LLNL also briefly considered a sidewise impact with a bridge abutment or similar structure. It concluded that the chance of such a contact was remote (compared to more likely collision scenarios) and, in its response to a criticism on this issue from LANL, stated that "this type of impact would be similar to that calculated for an impact with a train sill"[4] [i.e., the front of a locomotive chassis]. Absent a confirming calculated analysis or simulation, this opinion is not acceptable. A train sill impact involves contact over a very small area with an object having limited kinetic energy. A bridge abutment is essentially an unyielding column. Impact with it would yield a great deal of lead movement and bending stresses (as the cask ends continued to move while the center of the cask rapidly slowed down) not encountered in the case of the train sill. LLNL should have developed an analysis to show what speed was necessary to yield unacceptable strains due to bending and/or lead movement. The movement of lead also raises the question (even if the cask remained intact) of the gamma output at the point of contact with the column when the cask came to rest.

The Modal Study's analysis of the outer cask shell assumes that, at all points on its surface, it maintains its ability to yield to strain without breaking. As previously mentioned, real casks have numerous welds that may be weaker than pure steel. In addition, poor manufacturing techniques have provided other sources of cask vulnerability. One of the NAC-1 casks had a problem with uneven shielding, so copper plating was welded to the outside of the outer shell to increase shielding[20]. Not only would such surface welding affect the properties of the shell, but the presence of copper in contact with steel could create, at high temperatures, a melting eutectic point where copper would alloy with the steel, seriously weakening it. This modification only came to light after years of cask usage.

The strain from the drop onto a steel stump could not be duplicated (in the ... opinion) by a "real" situation. Only two "real" puncture scenarios were examined: a high speed perpendicular sidewise impact by the end of an I-beam, and collision with a train sill. In both cases, the Modal Study concluded that the shell and shielding would be severely dented but not penetrated. Based on these results, no further investigation of outer shell penetration was indicated. Thus, there was never any analysis of lead shielding loss due to a puncture followed by a fire.

While the basic simulation of striking a flat surface may be acceptable, the puncture study is not. The I-beam impact, for example, was limited to a beam whose height equaled the diameter of the cask. The original concept of the short fall onto the stump was to replicate a cask falling from its trailer (or flatcar) onto a railroad track (a form of I-beam)[21] The impact would then involve contact with the top side of a much smaller I-beam, not its end, and over a considerably different surface area. The train sill simulation was also open to question. While several impacts were simulated, all were perpendicular to the length axis of the cask: one was in the same plane as that axis, but the others were above that plane to varying degrees, providing glancing blows that would tend to rotate the cask around its length axis. The fact that neither simulation examined impact angles other than those perpendicular to the length axis is important: drop tests on steel stumps have found that the angle of greatest damage is not necessarily 90°. At that angle, strain around the circumference of the stump involves stretching an amount that is nearly the same at all points. At lesser angles, the strain is somewhat compressive on one side of the stump, and involves more stretching on the other.

In recent full-scale drop tests of a prototype Type B container (known as TRUPACT II), the outer shell (designed to a thickness that a computer simulation indicated was sufficient to avoid puncture) ripped on the side where stretching occurred[22]. This thickness of the shell was increased by about 25% as a result. The lack of sufficient analysis by the Modal Study leaves the potential for puncture an open question.

Lead Shielding

Failure to fully investigate puncture and cracking of the outer shell creates the rationale for avoiding consideration of the loss of shielding, a very serious potential problem. The only mechanism for major lead movement covered by the Modal Study is slumping due to an endwise impact of the cask onto a hard surface. Since opening of the outer shell may be a realistic possibility (due to puncture impact angle and/or poor fabrication), examination of the slumping effect alone is insufficient analysis upon which to base the rest of the study.

While other responses of the shielding have already been discussed in the context of the outer shell and insulating effects of the neutron shield, it is noteworthy to consider two more of its characteristics: alloying with steel at 1050°F, and its heat capacity.

As indicated above, absence of a neutron shield greatly accelerates heat transfer and the likelihood of rapidly reaching very high temperatures at the inner surface of the outer shell (as versus the delay inherent in melting most of the lead, which must occur before the lead mid-point temperature exceeds 620°F). Even if the exterior steel layer of the neutron shield was still intact, LLNL apparently did not examine the temperature at the point of surface contact between the lead and the steel outer shell and thus did not consider the potential for alloying at that point. Only when the lead mid-point temperature also reached 1050°F (see page 4-12) did LLNL consider alloying (at which point it indicated that damage was not quantifiable). Alloying of lead with nickel in the steel considerably weakens the shell and can affect its ability to expand under heat, possibly leading to cracking and creation of an avenue for lead loss. Only a very thin layer of lead needs to reach 1050°F for this phenomenon to occur, and LLNL should have determined when that point would be reached in order to properly assess its likelihood.

The heat capacity of lead creates another condition not covered in the Modal Study. All fire simulations in the Study examined the temperatures of the lead mid-point during the fire. Since the temperature of the spent fuel will always be lower at this time due to the buffering effect of the lead, a short fire that doesn't yield a mid-point temperature of 650°F during its duration is not considered to cause fuel rod bursting or oxidation. Examination of the temperature after the fire is out could be crucial, however, to assessing the fuel rod condition. A DOE-sponsored study by Pacific Northwest Laboratories (PNL-2588)[23] examined the fuel temperature during and after a fire and found the highest point was reached hours after the fire was out, due to the delayed heat transfer into the inner shell and the insulating effect of the lead. Very high temperatures resulted, sufficient to burst the rods. LLNL should have examined short fires that cause lead mid-point temperatures of less than 650°F to assess their delayed temperature at the spent fuel. If short fires eventually yield high internal temperatures, the likelihood for a significant release is heightened, since short fires are much more common than long duration fires (at least according to the distribution used by LLNL). This delayed heating effect will be discussed again when the spent fuel's response is also analyzed in a later section of this report.

In closing this section, it should be noted that loss of the gamma shielding would seriously hamper any efforts by emergency personnel, while greatly increasing their risk to exposure. At present, it is doubtful that most firefighters would conduct a careful, 360° radiological survey around a truck or train fire prior to approaching it, unless they knew the hazards of failing to do so when spent fuel is involved. Most firefighters do not carry the necessary equipment, and the DOT Emergency Handbook[24] does not suggest a circumferential radiation check prior to approaching a cask.

The Inner Shell

The inner shell creates the cavity to hold the spent fuel. It is also a cylinder that fills with water when spent fuel is loaded underwater (a requirement to contain its radiation). The previously mentioned drain and vent lines end at the inside surface of the inner shell. Many of the same comments concerning welding and ability to maintain strength while stretching apply also to this steel cylinder. The integrity of the inner shell has another important requirement, however. It must hold the fuel basket in place, remaining rigid and straight when compressed (as in an endwise impact of the cask against a surface). Impact simulations assume the inner shell remains rigid and straight, and thus does not provide any bending stress on the fuel rods during an endwise impact. It may simulate such stress for a corner impact, but any previously existing bending would exaggerate such stress. While this type of assumption may be acceptable for an ideal case, it should be noted that the actual cask simulated by LLNL, the NAC-1 cask, suffered from a bowing of the inner shell. This problem was not confined to one copy of the container, but rather showed up in several of them[20]. Four out of seven NAC-1 style casks were taken out of service due to this problem, and it was not noticed until several hundred shipments had been made[25]. Had such a container been involved in a severe endwise impact, the bowing could have created a vulnerability to bending or buckling of the shell, which could damage the fuel rods, leading to leakage into the shell. Analysis of such potential weaknesses could give some idea if slight bowing would significantly compromise the shell's integrity. The lack of examination of such real cask problems only adds to the uncertainty of the Modal Study's results.

Penetration Sub-Systems

As previously discussed, the Modal Study did not consider in its damage analyses the various valves and tubing built into a cask. It was felt that valves were protected by design features (e.g., recessing below the surface) and that any damage due to a highly localized load would "limit the escape of any spent fuel material to that which can migrate or be driven out through the small diameter, tortuous passageways presented by the damaged penetration systems" (p. 3-16). While it may be true that chunks of spent fuel would be blocked by narrow cracks or by bends in the tubing, it is not chunks that are the problem. Rather, it is the vapors, gases and fine particles that may be inhaled which create a radiological hazard. Relative to them, any visible crack or tubing is hundreds or thousands of times larger, offering little resistance to dispersion.

Once again, however, reality and the actual NAC-1 cask provide a perspective on LLNL's avoidance of the penetration sub-system as an issue. Prior to their removal from service, at least two of the NAC-1 containers were found to have a chronic problem with valve closure. After several instances of casks arriving with valves open to the inner shell, it was found that the valves were installed backwards, due to confusing instructions[26]. Vibration of the vehicle while in motion apparently opened them. There was no need for a "highly localized load" to open them, nor would there have been a "tortuous path" for the particles, vapors and gases to negotiate.

Finally, the welds involved in installing the tubing also create vulnerabilities even without "highly localized loads." In drop tests without impact limiters, a cask suffered cracks in its welding along its drain lines that extended from the inner shell out to the surface of the container[27], even though the steel around the welds remained intact. Once again, assuming that welds will act just like unworked steel is simply not realistic.

Impact Limiters

While it is valid to model cask impacts with impact limiters, it would have been very useful to examine the situation if a limiter was not attached properly. The Modal Study assumed limiters and a truck cab (where appropriate) were both present to absorb much of the cask deceleration on impact. LLNL idealized the situation by assuming a perfect cask. The impact limiter is bolted to the end of the cask and is made of crushable wood. An impact at an angle could tear off the limiter, leaving the cask end vulnerable to a second impact (which present regulations do not consider). Such multiple collisions are not unusual in train derailments. The limiter is most effective for its first impact, after which it may be compressed and will not necessarily absorb as much impact. The NAC-1 was once found upon arrival missing bolts that attach its limiter, creating an opportunity for it to come off during an accident[28]. The Modal Study failed to consider such an eventuality, or to model the limiter bolts where they insert into the cask lid.

The Cask Seal

The Modal Study may have been conservative when it assumed that seal failure would occur if strain exceeded .2%, but there is no experimental data cited to support this number. A lower number may be possible. Furthermore, LLNL's thermal data appear to indicate that temperature at the seal would not reach the point of breakdown (about 500°F) but, as previously mentioned, the simulations appear only to cover the period while the fire is in progress (and while the neutron shield provides insulation), and not thereafter when the delayed thermal transfer could be significant. The cask seal does, however, possess a particular vulnerability not evidenced by the other materials. Unless it is a metal seal, it can be dissolved. It is not hard to imagine a rail cask as part of a typical commercial freight train (assuming that dedicated trains are not used*) that also carries a variety of chemicals, some of which may be solvents to the seal. A derailment involving leakage of such a substance could threaten the seal, and no major impact would be needed. A small fire could then provide heat to drive gases out of the cask, perhaps carrying with them particles of fuel surface crud. The Modal Study considered only impact and fire as means to damage the seal.

Final Comments on the Realism of the Modal Study's Cask

LLNL made several simplifying assumptions that, unless closely examined, could be the sources of unseen problems. For example, when simulating the type of steel used in the cask, LLNL used a slightly different variety than that actually in service, apparently due to limitations on its available data. Insufficient information is provided to assess possible

* Northern States Power Company and the Nebraska Public Power District recently used dedicated trains in two of the largest shipping campaigns in commercial nuclear power history. In the 1988 OCRWM Draft Mission Plan Amendment, DOE assumes that shipments from a monitored retrievable storage facility (MRS), if constructed, will be made by dedicated train (i.e., trains containing only spent fuel as cargo). There are, however, no regulatory requirements for mandating dedicated trains. There is also considerable sentiment within nuclear utilities and DOE defense programs that dedicated trains are unnecessary. Moreover, OCRWM has carefully avoided any commitment to use dedicated trains for shipments between reactors and the MRS, or between reactors and a geological repository, if the MRS is not built. Therefore, it cannot be assumed that current (or next) generation casks will not be shipped in general freight service.

impacts of this alternative choice. Another simplification involved one of the drop simulations. During the sidewise impact of a rail cask on a flat surface, the sheer weight of the shielding nearly flattens the container (see p. 7-9 and Appendix E). It is extremely hard to imagine the welds to the end of the cask not yielding completely in such a case, creating a large avenue for release of fuel chunks and for direct exposure. Unfortunately, the simulation is only two-dimensional, and does not include the mating surface between the cask body and its ends. LLNL should have simulated that surface to determine the likelihood of lid separation. Instead, it simply assumed that releases from severe unsimulated scenarios would be ten times greater than for those it had analyzed.

In several other places, LLNL refers to full scale tests used to verify or benchmark simulations of accidents. In two important cases, it chose to avoid mention of the problems these tests revealed about proper cask fabrication. As previously covered, the failure of an outer shell during a fire test is not discussed. Even worse, however, was a reference to British rail crash tests. Citing the lack of damage involved, LLNL (on p. 6-32) leaves the impression that this test confirmed its analysis. Once again, reality is ignored: the cask in question was a solid forged design, not the welded steel and lead sandwich simulated in the Modal Study. Unmentioned is the fact that the British subjected some of their older welded casks to drop test and found that they cracked along their welds, contrary to the results of their simulations[29]. To their credit, the British retired those containers and now use only forged steel casks. If the British tests demonstrate anything, it is that cask welds are a source of vulnerability, therefore disproving the Modal Study's use of strain as its primary mechanical variable, and supporting LANL's criticisms.

3. Accident Scenarios

10CFR71: Starting at the Destination

LLNL examined a number of accident scenarios, using the 10CFR71 performance tests (i.e., drop, puncture, fire) as a starting point. LLNL discounted the need to examine criticality after a collision and immersion in water (the final 10CFR71 test), because its probability calculations indicated that such a scenario would occur only once in ten million years. In some ways, paralleling the present regulatory scheme made the Modal Study's goal of verifying it almost a self-fulfilling prophecy. It is important that the reader avoid also "signing on" to the 10CFR71 perspective while thought is given to the potential accident conditions that could realistically prevail. The degree to which LLNL did so will become obvious and, to that degree, the Modal Study loses some of its credibility.

But focusing on the order and types of those tests was not the only problem with LLNL's accident scenario analysis. The Modal Study's simulations failed to realistically simulate some characteristics of drops, collisions and fires, and other possible scenarios were deleted from the analysis without sufficient examination. LLNL also failed to sufficiently interact the effect of one accident condition with those that followed it.

The 10CFR71 tests were designed as highly simplified simulations, not of actual accidents, but of the worst conditions that could prevail in almost any accident. LLNL "translated" them into its own parameters of strain and temperature which, it believed, could be used to categorize an accident's potential for causing a radiological release. As previously covered in the "cask response" section of this report, the strain and temperature considerations are themselves highly simplified replications of reality, also somewhat open to question. For the moment, however, the concept of the conversions to strain and temperature will be accepted.

Collision Simulated by Dropping

The 10CFR71 tests first call for dropping a container, in its most vulnerable orientation, onto a flat unyielding surface from a 30-foot height. Since there are no totally unyielding surfaces (i.e., all real objects will absorb some impact energy), it was essential for LLNL to model a number of "real" conditions and determine the collision speed necessary to equal the kinetic energy that the cask body would absorb in the idealized 10CFR71 drop. This process is referred to as the "equivalent damage" technique. LLNL found that an impact with soft soil would require an impact speed in excess of 150 mph, an unrealistic velocity for a truck under any condition. Hard soil and rock required lower speeds, as did some concrete structures. This approach is acceptable from the standpoint of screening out some types of accidents (e.g., hitting a mound of earth) but only looks at total energy transfer. The most vulnerable angle and point of impact are more difficult to determine.

LLNL considered side drops (i.e., impact at 0°) and end drops (90° impact) and then interpolated linearly between those angles to assess the conditions that would prevail for drops on a corner of the cask. This simplification could lead to a significant error. In the review of cited references and others known to this writer, it became obvious that the determination of the most vulnerable angle and point can only be done with surety through experimentation. One reason for this is the "slap down" phenomenon previously mentioned, in which a drop on one corner results in acceleration of the other end of the cask as it revolves prior to its own contact with the impacting surface. The increase in velocity for the secondary impact (which may also occur at a different angle) may be considerable, and could depend on such items as the flexibility of the impact limiters and location of the cask's center of gravity. The software used by LLNL does not model this phenomenon.

The Modal Study analysis concluded (p. 4-7) that only a .2% strain level would occur at the inner shell during the 30 mph impact (i.e., the 30 foot drop) onto an unyielding surface, so no seal damage would result. Impact speeds of 35 to 55 mph would yield the same result on hard rock, depending on the impact angle (i.e., orientation of the cask to the surface) (p. 6-30). At higher velocities, the strain would no longer be elastic and seal failure is assumed. Note that the impact velocity assumed is that of the first corner to land, not the second corner, which may be moving at a higher speed in a corner drop. Furthermore, the cask lid and body are two separate objects connected by bolts that can flex and bend, so the assumption that distortion of the inner shell is the only criterion for seal failure may be insufficient. In light of these uncertainties, LLNL's conclusion that no seal failure will result at or below the first 10CFR71 drop cannot be accepted without a more dynamic analysis at points along the seal of the cask lid.

Interacting the Effects

Other aspects of the impact with a flat surface also appear to have been simplified, or else were not taken fully into account in later tests. For example, imagine a rail cask involved in a fall onto its tail end, followed by a fire near its lid end. In such a case, lead will have slumped to the rear, removing that heat sink from near the cask seal. One accident condition then creates a worsened (and unexamined) situation for a later aspect of the scenario. Similarly, a side drop onto a hard surface can so distort a cask's shape that the lead will become thinned on the sides of the cask and continued connection with the end plate is doubtful. While the integrity of the lead may remain immediately after the drop (though now thinner at some points), it is now vulnerable to loss (through the damaged end plate connection) when the lead becomes molten in a fire. While LLNL may say that such a fire must exceed the 10CFR71 limit of 30 minutes and is statistically unlikely, recall that this same phenomenon (of cask flattening) will also flatten the empty neutron shield, eliminating much of its insulating capability. Heat transfer rate is increased, possibly to the point that a 30 minute fire is no longer essential to begin lead melt. Many other such cases can be posited, the likelihood of which are not known with any accuracy due to limitations on accident data and/or the simulations. Nevertheless, they have potential for occurrence and these interactions were ignored by the Modal Study even when (as in the case of cask flattening) it postulated the initial step itself.

It may be argued that such combinations are covered by "conservatively" assuming that they fall into the region beyond 2% strain and 650°F fires, where the radiation release is assumed to be 10 times greater than in the next least severe range. Once again, however, the statistical juggling done to marry the impact strain to lead temperature leaves one uncertain as to its validity. The distributions of the two characteristics were combined with very little linkage between them, and their origins were from two different data bases. Even if this data is accepted on faith, however, the multiple of 10 for a release quantity has no basis and, in the postulated flattening case, could easily be off by several orders of magnitude due to increased exposure alone, if the lead shielding were reduced by slumping, or by melting and subsequent lead loss. Failure to follow through on these interactions is a major shortcoming in the Study and again demonstrates its underlying lack of reality.

Potential for Puncture

The possibility of puncture of the outer shell was, in effect, ignored by LLNL's analysis. As previously discussed, simulations involving an I-beam and a train sill were apparently sufficient to convince LLNL that puncture of the inner shell was not within the realm of possibility. While it may be likely for the inner shell to remain intact (though the cask seal has been assumed to leak at 2% strain that results from a 27 mph impact by a train sill), there is also a need to examine the condition of the outer shell. Puncture of the outer shell would open a pathway for molten lead leakage, increasing direct exposure and removing a thermal barrier from the inner shell. As previously discussed, this affects the size and duration of a fire needed to further damage the inner shell, seal and fuel.

LLNL used NIKE-2D, a finite element computer code, to simulate the I-beam and train sill impacts. While a major improvement over the empirical equation used to analyze puncture in most shipping cask safety analyses, NIKE-2D leaves a great deal to be desired, especially when strains in excess of .2% (i.e., inelastic) are involved. In a 1980 professional paper, NRC structural engineer R.C. Shieh criticized it, saying:

> "The NIKE-2D model also does not possess capability of modeling strain rate sensitive material on inelastic behavior. Therefore, additional efforts are required to improve the computational efficiency and dynamic modeling capability of rate sensitive materials (such as steel and lead) before the NIKE-2D model can become a useful tool in accurately predicting puncture behavior..."30

There is thus reason to doubt the validity of the Modal Study's quick dismissal of puncture.

It should be noted that experimental analyses (one of which was performed at LLNL in 1980) indicate that puncture of the outer shell of a lead-shielded cask is indeed a possibility and has, in the past, been underestimated by the empirical equation used in the design of most casks. An interesting finding of one study was that puncture required 50% less energy (i.e., could occur due to a drop from a lower height) after the shell had been heated to about 400°F than when it was cool[31]. A question then arises regarding the likelihood of a fire before puncture, instead of after, as outlined in 10CFR71. One need look no further than the 1978 Sandia fire test for evidence. During the fire, the cask was supported by a rail carriage which collapsed when its steel softened from the heat. The cask fell several feet into the steel rubble, showing how easily contact could be made with a rail track (or other protrusion). "Signing on" to the 10CFR71 order of things limited the Modal Study's examinations of real conditions that could have significant effect on cask integrity.

Concerns about Crush

As with puncture, the Modal Study casts aside any need to closely examine the potential for crushing a cask. While very few scenarios for crush are likely for truck casks (with the possible exceptions of a tunnel collapse or landslide), the rail environment provides several such opportunities. LLNL considered the 200-ton weight of a locomotive resting on-end against a cask, as the worst case and found it did not yield the same damage (p. E-11) as other scenarios. Major derailments can result, however, in greater weights being piled upon one railcar. An NRC study concluded the bounding value in such a case was 550 tons, nearly 3 times the case considered by LLNL[32]. Once again, it is hard to understand LLNL's failure to utilize (or at least comment on) relevant available data. This deficiency simply adds to the uncertainties surrounding its overall analysis.

Fire and "Smoke"

LLNL's attention to fire showed some effort to be conservative, and some of its analyses added valuable insight to this aspect of the problem. Once again, however, there are difficulties with its acceptability. Several problems associated with the interactions of fire and other accident conditions have already been covered, and the simulation of heating the spent fuel will be covered in the next section. For the moment, it is necessary to focus on the fire simulation's underlying assumptions.

While the typical flame temperature assumed may be realistic, the sheer number of assumptions inherent in describing the fire duration, location of the cask and types of flammable materials places the result firmly into the probability "ether." The Sandia analysis used as basis for some of this input (SAND74-0001) is itself based on many (a total of 26) "best guesses," plus some rather old references[33]. It is noteworthy that the data used in that study is significantly dated with regard to types of flammable materials now shipped, the traffic of such materials and the accident rates involving them. It is unclear why LLNL did not try to update the input by using more recent data sources (e.g., the DOT Hazardous Material Information System), but its lack of effort in this area (or any effort to benchmark the result against such data) leaves its fire severity distribution shaky, at best. For example, while much of the flammable material shipped by road and rail is heating or vehicle fuel (the "worst" case included in the Sandia analysis), an increasing amount consists of very high flame temperature materials used in industrial processes (e.g., benzene, propane, acrylonitrile)[11]. Stationary sources of fuel (e.g., storage tanks and pipelines) are also ignored despite the fact that such sources could yield extreme conditions near road and rail lines, as previously discussed under "Data Creation and Analysis." As a result, LLNL's analysis lacks conservatism in its probability assumptions regarding temperature and duration.

Another unsettling aspect of the fire simulation is the disregard for a torch fire. LLNL sets aside any such concern by focusing only on the total thermal input to the cask. LLNL reasoned that, because a torch fire only strikes a small area of the container, it cannot do nearly as much damage as an engulfing fire that transfers a massive amount of thermal energy to the cask. Again the "blinders" inherent in the 10CFR71 approach appear to have blocked awareness of the interactions of accident conditions. While total thermal energy may be a fair way to dismiss the immediate effect of a torch fire on the inner shell it ignores the effect on the outer shell. A 1980 Sandia study of torch fires noted the following:

> "Non-uniform heat input in real fire exposure environments could lead to a number of package design problems unless care is taken by the designer. Local stresses could result in package or seal failure. Also, lead gamma shield material could melt locally away from expansion volumes and the outer shell could rupture, allowing the gamma shield to be totally or at least partially lost."[34]

Loss of a portion of the lead shielding could then expose part of the inner shell to severe local heating, all without raising the average mid-lead temperature to 500°F. Torch fires on railroads are common enough to require that railroad propane tankers be able to withstand them, under DOT regulations[35].

The Modal Study is therefore unfortunately deficient in its examination of several important fire scenarios that could affect the integrity of the inner and outer shells. Coupled with the difficulties previously outlined on its assumptions of a thermal barrier in the empty neutron shield, it is not hard to conclude that there is serious potential for the Study to be a source of erroneous conclusions on the fire resistance of its representative cask.

Taken individually or in toto, these problems show that the Study's portrayal of accident scenarios leaves a great deal to be desired. Its failure to interact the results of different, but consecutive, accident conditions makes some of its results unreal. Combined with its idealistic and highly simplified view of the cask response, one is left with little confidence in some of its conclusions in this area.

4. Spent Fuel Responses

Examination of the Modal Study's radiological release assumptions also finds numerous reasons for concern. Some of them relate to apparent ignorance of past studies and incidents, while others reflect the potential impacts of problems previously outlined in the "cask response" and "accident scenario" sections of this paper. Unfortunately, the appendix gives no supporting discussion in this area, so the reader is forced to perform research to add perspective to LLNL's conclusions.

Missing Sources of Radiation

The Study lists the isotopes that it considers significant to a possible release (p. 8-6), without benefit of reference. Examination and comparison to other studies of spent fuel confirm the list with two major exceptions:

- americium 241 (Am-241) is missing
- there is no attention to gamma emitters in the structural part of the fuel assembly.

The absence of Am-241 may have resulted from examination of isotopes that exist when fuel is first removed from the reactor. Am-241 does not represent a major nuclide at that time, or even 150 days later, when most past spent fuel transport studies examine the fuel's inventory. Over several years (and especially between 5 and 10 years), however, plutonium 241 decays to Am-241, increasing the americium curie strength nearly 100 times[36]. As a potentially hazardous aerosol, it is as dangerous as any of the isotopes of plutonium, and at 5 years provides a significant portion of the total hazard. If it is actually absent from LLNL's analysis (and not merely a major typographical error missed during all reviews and edits), there is some question about the care taken elsewhere in the Study's radiological analysis.

The failure to include gamma emitters in the structural parts of the fuel is not related to an actual release of materials, but rather is of concern when analyzing direct exposure after lead slump. The end piece and foot piece (see figure 8-1 in the Study) are composed of steel containing cobalt, some of which has been converted to Co_{60} after years in the reactor. Other components of the steel have been similarly converted but do not represent the same hazard as Co_{60} due to their amount, or rapid decay. When an endwise impact of 46 mph was examined, a lead slump of about 3 inches occurred for a truck cask, and about 6 inches for a rail cask. These speeds occurred at the the 2% strain level. Figure 8-7 indicates that (absent any thermal effects) exposure of only .36 curies would result for the truck cask and 27.5 curies for the rail cask. The only way this could conceivably occur is if no curie content was attributed to the head piece of the assembly, a good portion of which would be exposed during such a lead slump. Figure 8-1 indicates LLNL considers the "active length" of the assembly to begin somewhat below the head piece, which would support this conjecture. The head piece, however, contains more than half of the approximately 2000 curies of Co_{60} in one assembly and gives off (even after 5 years out of the reactor) several hundred rems per hour of gamma radiation, when unshielded[37]. The Modal Study's calculated hazard due to lead slump is inconsistent with this data, which is based on actual measurements of aged spent fuel assemblies. It should be noted that the neutron output of radiation at the head end of a fuel assembly is so intense that, over time, it caused conversion of cobalt in the steel in the lid of an IF-300 cask, causing it to give off an unacceptably high level of radiation on its own[38]. In light of these facts, the direct exposure aspect of the Modal Study requires major revisions.

While it may be just an unintentional omission, fuel crud (i.e., the radioactive surface dirt on the outside of the cladding) and its characteristics are never discussed in the Study; it is only mentioned as a footnote on p. 8-2. This raises an additional question: was crud treated the same as the other isotopes, only to be released when the cladding was breached and fuel pellets damaged? There is evidence of this when one tracks the calculations leading to figure 8-7, in which the released curies are delineated for each of the response regions. Table 8-3, which lists the release fractions due to rod burst or oxidation, appears to be the sole basis for development of figure 8-7, but a check of the reference cited (NUREG/CR-0722, hereinafter referred to as the ORNL study) shows that it was concerned only with releases from the fuel, not the crud layer[39]. If the crud was not "lost" during the analysis, LLNL needs to show why it does not appear in figure 8-7, since the data in that figure then forms the basis for the rest of its conclusions.

The amount of crud on an assembly has been found to vary with the reactor type, age, water treatment and other conditions. In some cases, it has exceeded 300 curies on a single assembly[40]. LLNL used only 21.1 curies. The crud analysis is important for three reasons:

- crud resides on the outside of the fuel, so no cladding damage is needed to release it to the cask environment
- it is shock and heat sensitive, so it can fall off the fuel during an impact, and starts to flake off the rods at only 212°F
- its particles are very small and can form an inhalable aerosol[40].

While the curie quantity of the crud is much less than that of the fuel, it is available for dispersal in the less severe (but much more likely) accident scenarios and requires no other chemical or other mechanism to form an aerosol. If crud release was not treated separately from fuel damage in the Study's analysis, then a large portion of the risk calculations are wrong and the Study's overall calculations and conclusions may be seriously in doubt.

How Much Cladding Damage and Fuel Leakage?

To estimate the fraction of fuel released to the cask environment, LLNL developed percentages of the rods damaged in each response region. It saw this as a two-stage process: the fraction damaged due to impact, followed by damage to the remaining rods due to thermal creep, a phenomenon related to heating of the cladding. To its credit, LLNL made a reasonably conservative assumption of the percent of rods breached in the .2% strain region due to impact, assuming 3% until the thermal creep temperature was reached. Its assumption of 10% damaged in the 2% strain region is, however, a guess not based on any tests. Some experimental verification is needed. In the 30% strain region, all rods are assumed breached and this guess is acceptable. LLNL also assumed that any nuclides released to the cask cavity would escape to the atmosphere, again a conservative assumption. LLNL's method of determining the extent of cladding damage and the fraction of nuclides released through broken cladding, however, leaves a great deal to be desired.

To estimate the damage to shock, LLNL used data from a 1979 ORNL study aimed at analyzing spent fuel's response to a loss of coolant accident (LOCA) while still in a nuclear reactor. Only thermal (not impact) conditions were involved when very high temperatures (900 to 2200°F) were imposed on spent fuel out of the reactor for about 2 1/2 years. Damage resulted from pressure buildup in the rods, causing them to perforate (i.e., burst through a small hole). The gases, vapors and particles that escaped were measured, and release fractions developed. LLNL states (p. 8-12) that it used the results of those experiments to estimate its own material release fractions. Close comparison of the Study's fraction (Table 8.3) and the ORNL data show significant discrepancies, however, the worst of which involves the fraction of particulate material released. Since most of the dangerous curies are in particulate form, this difference could have a major impact on the degree of hazard. Specifically, the ORNL study found that an average of .02% (i.e., 2×10^{-4}) of the fuel escaped in particulate form, while the Modal Study used 2×10^{-6}, only one-hundredth as much. Unfortunately, the Study does not provide any formulae or calculations to explain the difference. Efforts by this writer to duplicate possible qualifying assumptions were unable to arrive at this factor. For example, the ORNL tests found that each one-foot-long test segment depressurized through a small hole, about 1/16 inch in diameter. If LLNL assumed that a 15-foot rod would also perforate through only one such hole, then the release fraction should be 2×10^{-4} divided by 15, or 1.33×10^{-5}, but this is still about 7 times too high. Correcting for the age of the ORNL fuel (2 1/2 years instead of 5) made a slight difference, but arriving at the Study's fraction was only possible when erroneous assumptions were made.

But this "mystery" is compounded by another: the radiological hazard figures for particles in figure 8-7 do not agree with the basic calculation involving even the 2×10^{-6} release fraction. For example, region R(1,3) (where 100% of the rods are damaged) shows 7.22×10^{-3} curies of particles. Since more than 100,000 curies from the isotope inventory in Table 8-1 could be in particulate form, one would expect at least 100,000 x (2×10^{-6}) curies (i.e., .2 curies) to exist as R(1,3) particles. Again, no basis for this factor of 28 was indicated, nor could one be developed. The Study numbers therefore differ by a factor of at least 28 x 7 = 196 from any straightforward method to adjust the ORNL data. Similar discrepancies were found in some of the calculation of releases of gases and vapors. Until its exact methodologies and calculations are checked by independent reviewers, these results are, at best, suspect. It should be noted that neither peer reviewer was given this information, and the primary reviewer commented several times on the large number of assumptions hidden in the calculations.

Let us assume (for the moment) that all calculations are correct, however. There still remains the validity of using the ORNL thermal test data as a substitute for impact data. As indicated above, the damage occurring in the ORNL tests consisted solely of a single 1/16 inch diameter hole in each rod. There is no theoretical or experimental analysis to confirm such a uniform and low level of damage due to all degrees of impact[41]. To the contrary, rods have become brittle in reactors, have broken while being moved, have come loose from their frames and have leaked in casks - all without involvement in a major impact[42]. Furthermore, all the ORNL tests yielding usable particle data involved a steam-helium atmosphere, containing only trace amounts of air. An accident in which a pathway to the environment exists would involve a major influx of air as the inert cask atmosphere diffuses rapidly out through the crack. Unlike steam and helium, air attacks uranium oxide at relatively low temperatures (above 400°F) converting it to U_3O_8 and breaking ceramic fuel pellets down into an aerosol powder[43]. Such action greatly accelerates release of gases and vapors locked into the pellet structure, while creating a form for the airborne release of all isotopes. The Modal Study implies that it examined oxidation by listing release fractions for gases and vapors related to oxidation in Table 8.3. It does not, however, mention that its basis for showing zero curies for particles resulting from oxidation originates from ORNL test procedures that involved no available oxygen to drive such a reaction.

Other problems exist with the use of ORNL data. At this point, the only conclusion one can come to is that, after a great deal of analysis in other areas, LLNL was confronted by an informational void and, instead of acknowledging that it lacked any valid release data, grasped at whatever it could find to fill the vacuum. LLNL understated the absurdity of its position on p. 9-23: "radiological hazards could be better estimated with pertinent tests performed at high impact conditions for the spent fuel rods."

Other Possibilities for Fuel Damage

Lost in the shuffle of suspicious data is, however, the actual thermal impact that could occur. As mentioned, the fuel pellets will decompose to powder when heated and contacted by the oxygen in air. Once again, LLNL's use of the mid-lead temperature diverts attention from the temperature of the inner shell and fuel. A prior study (PNL-2588) found that the temperature of the fuel will rise significantly hours after a fire is extinguished due to the delayed heat transfer of the gamma shielding (this is true whether it is lead, uranium or steel). The Modal Study gives no indication if it examined such post-fire conditions. Acceptance of the Study's exclusion of fuel oxidation from its release fractions is impossible without discussion of the phenomenon and the provision of post-fire simulation data.

It should be noted that fuel re-oxidation as a phenomenon has not been confined to the laboratory. In 1980, a fuel assembly with several damaged rods (one with cracked cladding) self-heated while in transit in an air-filled cask, breaking down a much larger portion of its fuel into powder than was seen in the ORNL steam-helium tests[44]. The cask (another NAC-1) was heavily contaminated and, when opened under water, released its powder via air bubbles that upon popping at the surface caused the powder to become airborne, contaminating the pool area[45]. Even after several decontamination efforts, so much powder remained in the cask that the mere draining of residual water weeks later cause major problems at a commercial power plant[44]. The area of fuel re-oxidation was so foreign to NRC regulators that they did not react to this incident until petitioned to do so by the Sierra Club. At that point (in 1984), NRC concluded that all casks carrying uranium dioxide fuel must contain an inert atmosphere, even when no cladding defects are detected, because of the difficulty in detecting such a weakness prior to the actual breech of the cladding[46]. There is thus good reason to doubt LLNL's conjecture that the worst shock damage a fuel rod will see is a single 1/16 inch hole over its entire length.

Several other characteristics of spent fuel may strongly influence its response to shock and heat. Both the ORNL test results and later work done at the Idaho National Engineering Laboratory (INEL) on fuel rod damage due to a major shock (i.e., from an explosion) found that the fuel pellets may shatter back to their grain size (i.e., the size of the particles of uranium before they are pressed and sintered into pellets). The particle size in question is in the aerosol range, making it very fine and able to pass through narrow cracks when airborne. If shock alone reduces some pellets to powder, then it is likely that LLNL's particle release fraction may be low by several orders of magnitude. For example, if only one pellet (out of nearly 100,000 per assembly) shattered back to grain, it could yield several curies of nuclides in dispersible form (as versus LLNL's 7.22×10^{-2} curies in the worst case).

While the cladding would still serve as a barrier to release of the powder, the cladding's own ability to withstand shock is also open to question. Zirconium alloy is designed to operate in water, not air, and will chemically combine with both oxygen and hydrogen, depending on the temperature. The metal may become brittle as a result, leading to cracks along its length, not just pinholes. It should be kept in mind that much of the fuel shipped in the future will have a history of dry storage as spent fuel pool capacity is exceeded and dry storage casks (using inert atmospheres) are increasingly presses into service. Cladding vulnerability appears to be closely tied to storage temperature and surface conditions, neither of which will be known with certainty until a much longer history of dry storage has been obtained.

If shock does yield cladding damage, there is a synergistic effect on re-oxidation, leading to further opening of the cracks or holes. The conversion of UO_2 to U_3O_8 due to heating in air is accompanied by a change in crystal structure and major pellet expansion as it decomposes. This action will spread cracks further apart, exposing more fuel to air, and so on. In the two ORNL air tests (neither of which were cited by LLNL), this began to occur but the expanding fuel eventually blocked the small hole resulting from overpressurization due to heating (but no impact). In the 1980 incident, a larger opening yielded a much greater release. As high temperature accelerates the process, it exposes more fuel surface and also accelerates gas, vapor and particulate release. While quantitative data on the overall impact of these simultaneous processes does not exist, such multiplying effects could quite easily increase released curies by much more than the factor of 10 assumed by the Modal Study for mid-lead temperatures above 1050°F.

LLNL attempts to diminish concern over gas and vapor release by repeating a comment on the potential for them to "plate out" (i.e., condense) as they contact cooler interior cask surfaces on their way to the atmosphere. This notion made sense when relatively "young" fuel (less than 1 year out of the reactor) was considered the norm for shipment, since it was always self-heating in the cask. Older cooler fuel, however, will be heated during a fire by radiation and conduction from the inside of the inner shell, thereby guaranteeing that the shell is hotter than the fuel. Since the cask is being heated from the outside due to fire, the vapors will experience a rise in temperature as they pass through cracks or tubing on their way to the cask exterior. Condensation prior to release only becomes likely during leakage occurring hours after the fire is out, as the cask surface cools off. Once again, the Modal Study's claims of conservatism don't withstand closer examination. As indicated in another study listed among the Modal Study's references (i.e., NUREG/CR-0811), much more experimentation and research on spent fuel responses is needed before assumptions regarding releases can be made with any credibility.

A Closer Look at Criticality

The last item regarding spent fuel's reaction to impact relates to the maintenance of sub-criticality during and after an accident. Changes to fuel configuration can cause criticality if accompanied by intrusion (or presence) of a moderator such as water. The Modal Study dismissed the chance of such an occurrence as once in ten million years (p. 9-25), using the probabilities in section 5.0. These numbers assume a major impact followed by submergence in an existing body of water. Other combinations of events could, however, mimic aspects of that seemingly incredible scenario. As discussed on p. E-89, "...the rail cask is like a thin-walled cylinder. Under the severe impact conditions, it is unable to support itself." Sidewise impacts with a surface or rigid abutment at high speed could yield collapse of the rail cask inner shell onto the fuel, reconfiguring it into a number of different densities. The same impact could cause the weld to the end cap to crack, thereby creating a path to the fuel. While it is agreed that simultaneous submergence in a body of water would be very unlikely, such an eventuality is not essential to create the criticality scenario. Any fire, even a small gasoline blaze, may prompt firefighters to apply water, thereby providing the necessary moderator. The cask may also contain residual water after loading: such is allowable with rail casks (the IF-300 may hold a number of gallons) and a NLI 1/2 cask - designed to be shipped dry - was once (due to a human error) shipped full of water while containing spent fuel)[48]. It is therefore not essential for a fire or even a cask breach to exist in order for the proper combination of factors to occur. The apparent ignorance of LLNL personnel with respect to actual cask operations and history also apparently blinded them to cases where sub-criticality was not guaranteed by design. After a number of years of use, several spent fuel casks and one plutonium container (all certified by DOE) were found to be vulnerable to uncontrolled criticality in an accident, and were taken out of service[49]. Nor has NRC certification been perfect in this regard. A mathematical error in the design of the IF-300 BWR fuel basket could have caused buckling in a crash, thereby limiting its ability to control the fuel rod configurations[50]. The error was not found until many shipments had occurred, fortunately without a crash. Luckily, the original design analysis was so crude that the math error was later found to be smaller than needed to create a serious hazard. The same mistake in a more sophisticated analysis could have yielded a very different result. Criticality loss cannot be simply wished away by considering only a highly unlikely accident scenario.

The same appendix E discussion also provides a glimpse into another potential limitation on the Modal Study analysis. Unlike truck casks, "the mass of the rail cask contents is very large compared to the mass of the cask...contents are very important to the rail cask calculations and should be modelled to provide more accurate impact forces and g loads and to support the cask as it collapses." (p. E-89) The pressure of a collapsing lead wall could significantly rearrange the fuel rods and perhaps move or damage any moderating poison rods in the fuel assembly. None of the Modal Study cask models included contents. The forces of the collapsing lead wall as it struck the fuel would provide useful input to analyzing possible cladding and pellet damage, and questions the assumption of a 1/16 hole as the maximum extent of a cladding breach.

In conclusion, the lack of effort by the Modal Study participants to study the response of fuel to shock, temperature and physical/chemical interactions is disappointing, at best. There is a wealth of data on the potential for cladding and pellet damage in air, done to analyze dry storage[51]. These sources are not listed in the Study's references, and one assumes they were not consulted. Yet, in the end, it is the fuel that is the hazard. Spending almost all of its attention on the container and the accident, the Modal Study lost sight of the cask contents, creating a large residue of uncertainty and the possibility that its consequence analysis lacks credibility. Since consequence is half of the risk analysis, the Modal Study has failed to complete its task - and thus has failed to confirm the 10CFR71 standard it sought so desperately to support.

Relevance to Shipments to the Yucca Mountain Repository

Since the Modal Study was published, numerous changes in cask payload and design, as well as the number of shipments, have occurred. While LLNL attempted to be conservative by choosing the design it felt was most vulnerable, some of the changes are not covered by its choices.

LANL pointed out, for example, that strain is even less useful as an indicator when harder gamma shields are involved. Uranium shielding will not yield easily, thereby passing on almost all force directly to the cask's seal and welds. It will also alloy with steel, but will not easily melt, therefore not acting as a heat sink to the same degree as lead.

As mentioned, water neutron shields have been replaced by solid materials that will not have the same thermal characteristics as the dead air space assumed by LLNL. Thinner gamma shields will be used because of the decreased gamma output of the older fuel, more of which will be carried in each cask. Such fuel will probably have a higher burnup rate and will therefore have a higher isotope concentration. The cask-to-payload weight ratio will decrease significantly, making the Modal Study's "no payload" simulations even less relevant.

The mix of shipments will be different since nearly half the reactors lack rail spurs, despite early assumptions that most would utilize rail transit. The total number of shipments may be reduced by the larger capacity of the casks, but that factor also aggravates the direct exposure problems after lead slump (if lead continues to be used).

Likewise, the state of information on fuel conditions has improved, due to the advent of dry storage and rod consolidation research. The high cost of computer power has dropped precipitously, so better and more detailed simulations are possible within a realistic budget. Finally, the Nuclear Waste Fund provides a ready source of capital to perform an improved, updated and more realistic Modal Study.

Conclusion

All of the above considerations point toward the need - and opportunity - for a clearer look at cask safety. The Modal Study was a necessary step in that direction, but not a sufficient one. It needs to be redone and its methodology and results closely critiqued by a competent body of reviewers while it is in progress, if credibility is the desired final result. The present document is unable to satisfy even a brief critical examination. Its flaws provide a breeding ground for bad decisions, from which in the future all parties may suffer.

References

1. "Programs for Ensuring the Safe Transportation of Hazardous Materials Need Improvement," CED-81-5, U.S. General Accounting Office, Washington, D.C., November 4, 1980
2. "Peer Review of Report Entitled 'Shipping Container Response to Severe Highway and Railroad Accident Conditions', M. N. Plooster et al, Denver Research Institute, Denver, CO, September 9, 1986
3. Letter, M. N. Plooster (DRI) to R. F. Mensing (LLNL), September 2, 1986
4. "LLNL Responses to Peer Review Comments on NUREG/CR-4829," L. E. Fischer, Lawrence Livermore National Laboratory, Livermore, CA, January 16, 1987
5. "A Review of the Structural Analysis Supporting the Report 'Shipping Container Response to Severe Highway and Railway Accident Conditions',", J. G. Bennett et al, Los Alamos National Laboratory, Los Alamos, NM, August 22, 1986
6. Letter, M. N. Plooster (DRI) to William Lahs (NRC), September 12, 1986
7. "Scale Model Drop Tests to Evaluate Impact Response of Lead and Uranium Shielded Radioactive Material Shipping Containers," BMI-2039, J. A. Hadden and R. J. Burian, Battelle Memorial Institute, Columbus, OH, September 30, 1979
8. "The Effects of Drop Testing on Scale Model Shipping Containers Shielded with Depleted Uranium," LA-8120-MS, Los Alamos Scientific Laboratory, Los Alamos, NM, February, 1980
9. "Evaluation of Analysis Methods for Type B Shipping Container Impact Problems," LA-6640-MS, J. Counts and J. B. Payne, Los Alamos Scientific Laboratory, Los Alamos, NM, January, 1977
10. "Transportation of Hazardous Materials," Office of Technology Assessment, Washington, D.C., July, 1986
11. "The Next Nuclear Gamble,", M. Resnikoff et al, Council on Economic Priorities, New York, N.Y. 1983
12. "Railroad Safety: FRA Needs to Correct Deficiencies in Reporting Injuries and Accidents," U. S. General Accounting Office, Washington, D.C., April, 1989
13. "Social and Economic Aspects of Radioactive Waste Disposal,", National Research Council, National Academy of Sciences, Washington, D.C., 1984
14. "Chemicals on Rails: A Growing Peril," John Cushman Jr., New York Times, New York, N.Y., August 2, 1989
15. "California City's 2nd Disaster in 2 Weeks," Robert Reinhold, New York Times, New York, N.Y. May 26, 1989
16. "Soviet Gas Pipeline's Explosion Reportedly Kills at Least 500," Bill Keller, New York Times, New York, N.Y.. June 5, 1989

17. "Transportation of Radionuclides in Urban Environs: Draft Environmental Assessment," NUREG/CR-0743, U. S. Nuclear Regulatory Commission, Washington, D. C., July, 1980
18. "Chemical Engineer's Handbook," R. H. Perry and C. H. Chilton, McGraw-Hill Book Company, New York, N.Y., 1973
19. "Post-Mortem Metallurgical Examination of a Fire Exposed Spent Fuel Shipping Cask," SAND-77-1424, Sandia National Laboratory, Albuquerque, NM, April, 1980
20. NRC Order to Show Cause, April 6, 1979 and NRC Inspection Report 99900331/79-01, August 31, 1979, U. S. Nuclear Regulatory Commission, Washington, D. C.
21. "How Some of the Package Tests Were Conceived," R. F. Barker, Seminar on Transport Package Test Standards, Tokyo, Japan, October, 1981
22. "Safety Analysis Report for Packaging, TRUPACT-II,", U. S. Dept. of Energy, Washington, D.C., 1989
23. "An Assessment of the Risk of Transporting Spent Nuclear Fuel by Truck," PNL-2588, Pacific Northwest Laboratory, Richland, WA, November, 1978
24. "Emergency Response Guidebook," U. S. Dept. of Transportation, Washington, D.C., 1984
25. Letter, Nuclear Assurance Corporation to NRC, Docket 71-6698, April 12, 1979
26. Letter, Wisconsin Electric Power Company to NRC, Docket 71-6698, July 21, 1977
27. "The Obsolete Cask Program: Drop Tests of the HWCTR Cask," L. B. Shappert et al, Oak Ridge National Laboratory, Oak Ridge, TN, 1978
28. Letter, Jersey Central Power and Light Company to NRC, Docket 71-6698, October 17, 1975
29. Central Electricity Generating Board press release, November 8, 1983
30. "Recent Developments in Puncture Analysis Techniques of Nuclear Shipping Container Components," R. C. Shieh, Gaithersburg, MD, 1980
31. "Puncture of Radioactive Material Shipping Containers," NUREG/CR-0930, Vol. II, U. S. Nuclear Regulatory Commission, Washington, D. C., June, 1979
32. "Potential Crush Loading of Radioactive Material Packages in Highway, Rail and Marine Accidents," NUREG/CR-1588, U. S. Nuclear Regulatory Commission, Washington, D. C., October, 1980
33. "Severities of Transportation Accidents," SAND74-0001, Sandia National Laboratories, Albuquerque, NM, 1976
34. "Assessment of Accident Thermal Tests and Analysis Procedures," SAND-80-0060C, Sandia National Laboratories, Albuquerque, NM, 1980

35. Code of Federal Regulations, 49CFR197.105-4(c)

36. "Final Generic Environmental Impact Statement: Handling and Storage of Spent Light Water Power Reactor Fuel," NUREG-0575, U. S. Nuclear Regulatory Commission, Washington, D. C., August, 1979

37. "Systems Impacts of Spent Fuel Disassembly Alternatives," BMI/ONWI-534, Battelle Memorial Institute, Columbus, OH, July, 1984

38. Memorandum, on irradiation of head end of cask, Docket 71-9001, 1983

39. "Fission Product Release from Highly Irradiated LWR Fuel," R. A. Lorenz et al, Oak Ridge National Laboratory, Oak Ridge, TN, February, 1980

40. "Comments of Fuel Crud as a Safety and Operational Factor of Independent Spent Fuel Storage Installations," NUREG/CR-0163, U. S. Nuclear Regulatory Commission, Washington, D. C., November, 1978

41. "A Scoping Study of Spent Fuel Transportation Accidents," NUREG/CR-0811, U. S. Nuclear Regulatory Commission, Washington, D. C., June, 1979

42. Proceedings of the 1983 PATRAM conference, page 806, May, 1983

43. NRC Research Information Letter No. 139, U. S. Nuclear Regulatory Commission, Washington, D. C., March 5, 1984

44. NRC I&E Report Numbers 50-213/80-20 and 50-219/80-38, U. S. Nuclear Regulatory Commission, Washington, D. C., April, 1981

45. "Airborne Contamination Released During Underwater Unloading of a Failed PWR Spent Fuel Assembly," R. W. Klingensmith, Battelle Columbus Laboratory, Columbus, OH, 1980

46. NRC Decision DD-84-9, U. S. Nuclear Regulatory Commission, Washington, D. C., April 13, 1984

47. "An Assessment of the Safety of Spent Fuel Transportation in Urban Environs," R. P. Sandoval et al, Sandia National Laboratories, Albuquerque, NM, June, 1983

48. "Directory of Certificates of Compliance," NUREG-0383, CoC No. 9010, U. S. Nuclear Regulatory Commission, Washington, D. C., 1986, and Letter, Duke Power Company to NRC, Docket 71-9010, December 1, 1981

49. "A Review of Human Reliability Issues in the Transportation of Spent Nuclear Fuel," L. Audin, Delos Associates, Woodstock, CT, May, 1988

50. Letter, General Electric Company to NRC, Docket 71-9001, September 7, 1982

51. "Workshop on Spent Fuel/Cladding Reactions During Dry Storage," NUREG/CP-0049, U.S. Nuclear Regulatory Commission, Washington, D.C., August 1983